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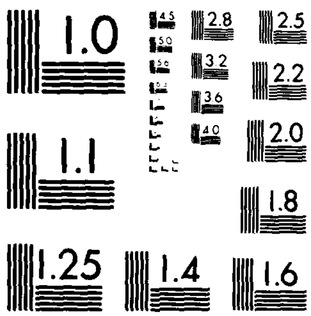

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MEMORANDUM REPORT ARBRL-MR-02994

SIMPLIFIED DETERMINATION OF RETARDATION FOR KINETIC ENERGY PROJECTILES

William F. Donovan

February 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Correspondence between experimental and analytical determinations of retardation is demonstrated for a particular flight projectile. The predictive model requires only the projectile physical dimensions and mass and presumes a linear drag coefficient characteristic.

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LIST OF SYMBOLS

A	reference area, $\frac{\Pi d^2}{4}$
A_{form}	fin form area
A_{sect}	sectional area of fin, $t\ h$
A_{wet}	wetted area
C_D	drag coefficient, $\frac{\text{Drag Force}}{\frac{1}{2}\rho v^2 A}$
F	drag force
M	mach number
N	number of fin blades
Q	operational parameter, $\frac{\rho A b}{2 m}$
R	operational parameter, $\frac{k M_o + b}{M_o}$
a	acceleration of projectile, $\frac{dv}{dt}$
b	intercept of C_D vs M characteristic
c_r	length of fin blade at root
d	reference diameter, 1.0 cal
h	height of fin blade
j	length of fin blade leading edge
k	slope of C_D vs M characteristic
ℓ_a	length of body
ℓ_n	length of nose
$\ell_{o.a.}$	overall length of projectile
ℓ_T	length of forebody, $\ell_a+\ell_n$
m	mass of projectile

LIST OF SYMBOLS (Cont'd)

s	distance along trajectory
$\dot{s}$	differentiation of s with respect to time
t	thickness of fin blade
v	velocity of projectile, $\frac{ds}{dt}$
$\dot{v}$	differentiation of velocity with respect to time
ρ	density of air

Subscripts

o	conditions at gun muzzle
1	conditions along trajectory

I. INTRODUCTION

Long rod kinetic energy penetrators often find tactical application in the particular aerodynamic environment of normal temperature and pressure and flat fire trajectory. This follows from the requirement of very high velocity, which implies a short time of flight and small gravity drop, and from the fact that the many tank battlefields of the world are at nominal sea-level altitudes. This circumstance permits some simplification to the calculation of the trajectory of proposed projectiles still in the preliminary stages of design and analysis. For preliminary design purposes, the Mach number excursion can be considered very short and the drag coefficient over the range of flight can be considered linear. The retardation then appears in closed form solution whereby, given the drag coefficient characteristic, the velocity becomes an explicit function of range.

II. PROCEDURE

In the free flight regime, the force balance along the axis of the zero yaw trajectory gives[1]

$$F = m \dot{v}$$

$$= - \frac{1}{2} \rho v^2 A C_D \quad (1)$$

where

F = axial force opposing the acceleration of the projectile,

$\dot{v}$ = the acceleration of the projectile,

ρ = the density of the flight medium,

v = velocity of the projectile,

A = reference area, and

C_D= drag coefficient.

The differential expression becomes

$$\frac{dv}{v} = - \frac{\rho A C_D ds}{2 m} \quad (2)$$

[1] *C. H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD #442757).*

where

$$\dot{v} = \frac{dv}{dt} ,$$

$$v = \frac{ds}{dt} , \text{ and}$$

s = distance along trajectory.

With

$$C_D = k\, M + b \ ,$$

where

b = intercept of C_D vs M characteristic,

k = slope of C_D vs M characteristic, and

$$\frac{dv}{v} = - \frac{1}{2\, m} \rho \ \ A \ (k\, M + b) \ ds = \frac{dM}{M} \text{ , since } M \text{ is proportional to } v,$$

or

$$\frac{dM}{M} = - \frac{1}{2\, m} \rho \ A \ (k\, M + b) \ \ ds \quad .$$

Upon integration (Appendix A) ,

$$M = \frac{b}{R\, e^{Qs} - k} \quad , \tag{3}$$

where

M = Mach number along trajectory,

s = distance along trajectory ,

$$R = \frac{k\, M_o + b}{M_o} \quad ,$$

M_o = Mach number at muzzle, and

$$Q = \frac{\rho\ A\ b}{2\ m} \quad .$$

With "s" the argument, M can be determined directly. This equation is presented in HP-97 program formulation in Appendix B.

An example will illustrate the application. Figure 1-a is an outline of a typical long rod penetrator (flechette) for which range data and measured retardation to 600 meters are available[2]. Figure 1-b shows an idealized model of this projectile with a simple fin. The corresponding experimental and calculated[3] drag coefficients are presented in Figure 2 where the range values represent turbulent flow conditions for small yaw flight. The viscous contribution to the calculated curve assumes turbulent flow friction factors but is posed for zero yaw and presumes a linear drag characteristic.

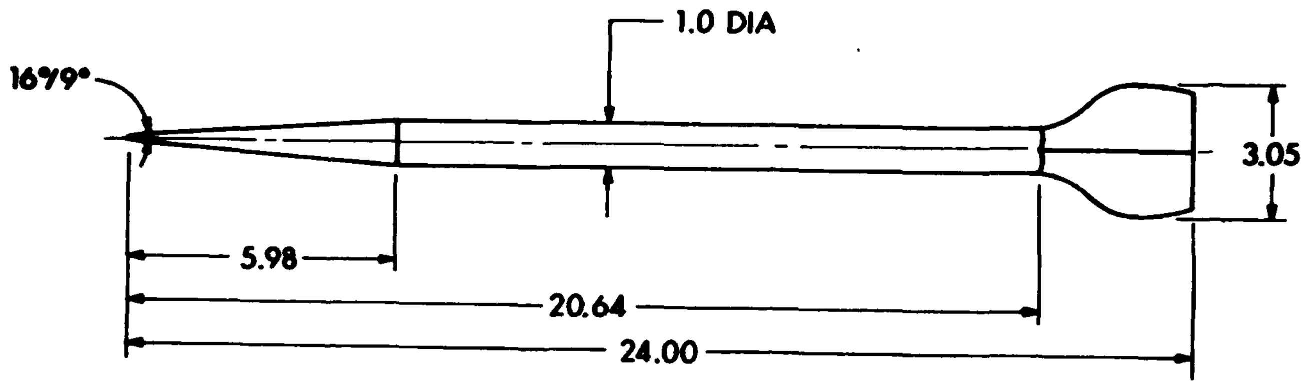
III. RESULTS AND CONCLUSIONS

In Reference 2, the experimental range velocities are presented to 600 meters (335,000 cal) with extrapolation to 1000 meters (536,102 cal). These data are transposed and values based on the linearized characteristic and Eq. (3) via Appendix A are given on Figure 3a and 3b for $M_o = 4.24$ and $M_o = 4.06$ respectively. The maximum deviation is within 3% over the full range.

Although discrete measurements for similar projectiles are not available for comparison, similar agreement may be expected.

[2] *Maynard Piddington, "The Aerodynamic Characteristics of a SPIW Projectile", BRL Memorandum Report 1594, September 1964.* (AD #355679)

[3] *William F. Donovan and Bertram B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978.* (AD #A054326)



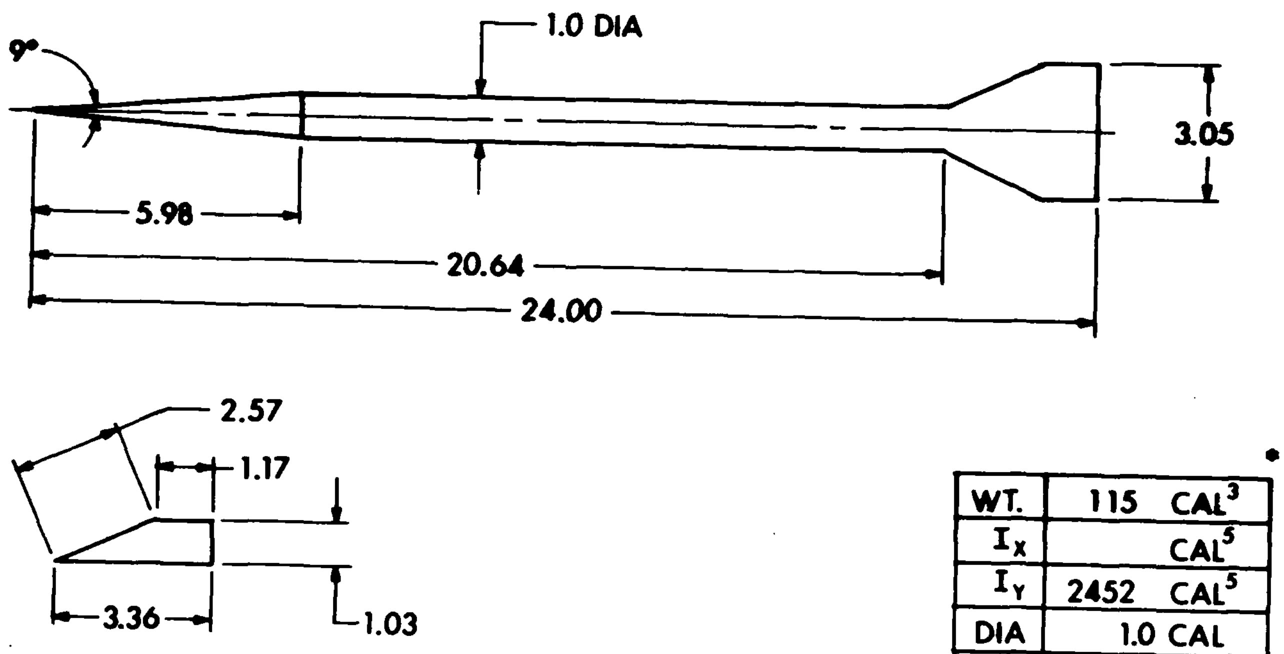
*

WT.	115 CAL^3
I_X	CAL^5
I_Y	2452 CAL^5
DIA	1.0 CAL
ρ	7.86

Figure 1-a. Outline of XM110 Projectile

SOURCE: Reference 2

* CALIBER NOMENCLATURE discussed in APPENDIX C



		*
WT.	115	CAL^3
I_X		CAL^5
I_Y	2452	CAL^5
DIA	1.0	CAL
ρ	7.86	

Figure 1-b. Outline of Idealized Model

* CALIBER NOMENCLATURE discussed in APPENDIX C

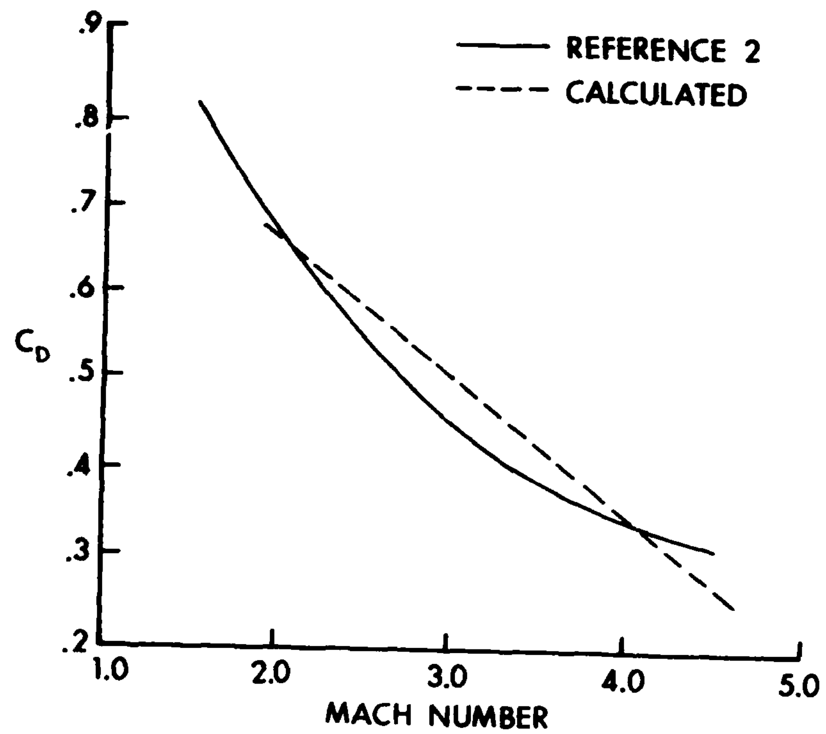


Figure 2. Drag Coefficient Characteristics

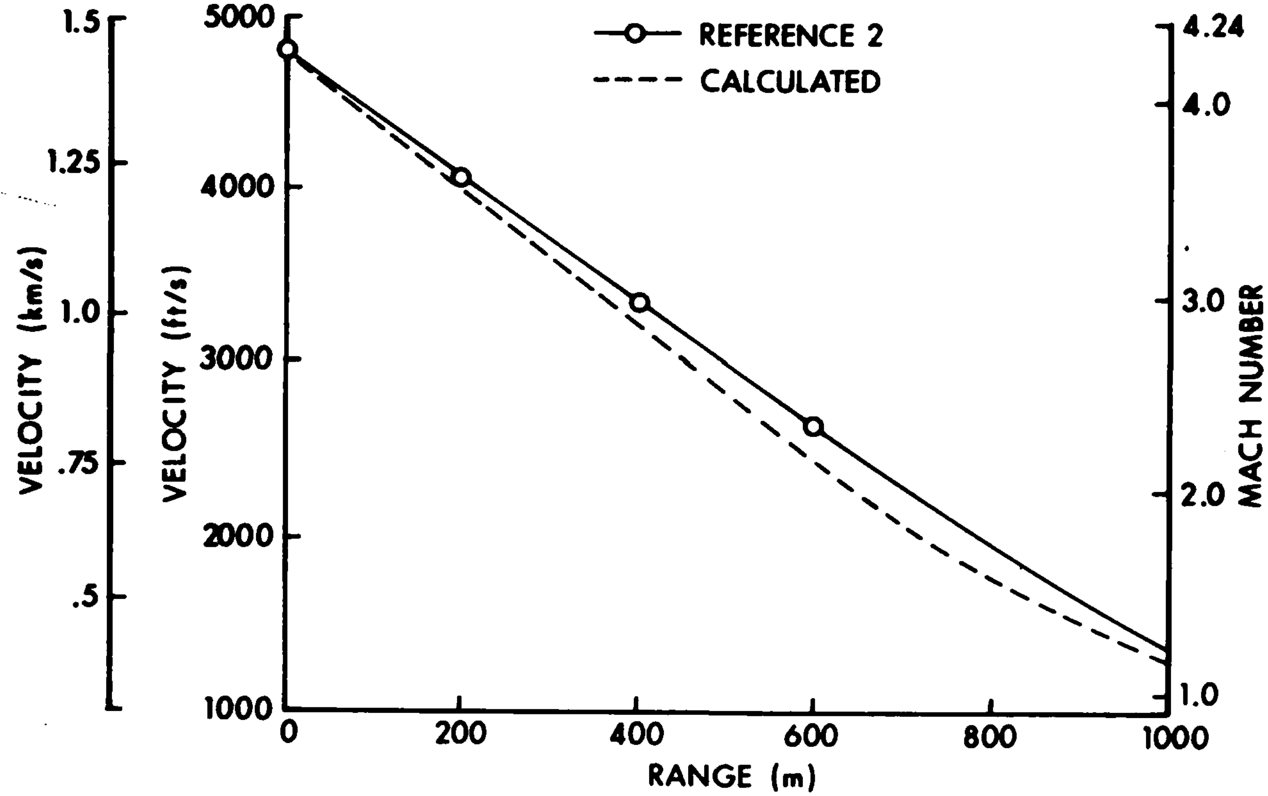


Figure 3-a. Velocity vs Range for $M_0 = 4.24$

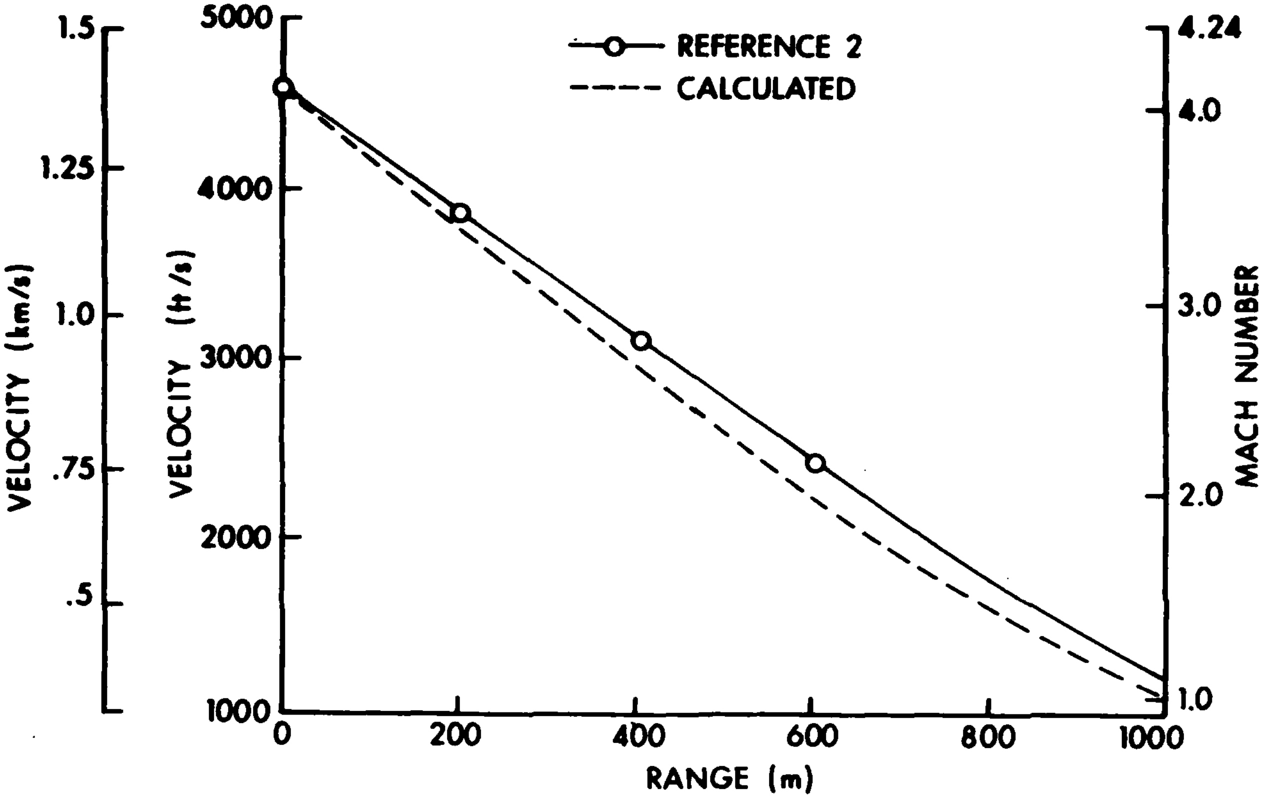


Figure 3-b. Velocity vs Range for M_0 = 4.06

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1. C. H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD #442757).

2. Maynard Piddington, "The Aerodynamic Characteristics of a SPIW Projectile", BRL Memorandum Report 1594, September 1964. (AD #355679)

3. William F. Donovan and Bertram B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978. (AD #A054326)

APPENDIX A

INTEGRATION SUMMARY OF EQUATION (3)

From Equation (2)

$$\frac{dv}{v} = -\frac{1}{2\,m}\,\rho\,A\,C_D\,ds$$

$$= -\frac{1}{2\,m}\,\rho\,A\,(kM + b)\,ds,$$

$$\frac{dM}{M\,(kM + b)} = -\frac{1}{2\,m}\,\rho\,A\,ds,$$

and #34 in Pierce's Table of Integrals* gives

$$-\frac{1}{b}\left[\ln\,\frac{k\,M + b}{M}\right]_{M_1}^{M_o} = -\left[\frac{\rho\,A\,s}{2\,m}\right]_{s_1}^{s_o}$$

which is easily verified by differention.

Then

$$\frac{\dfrac{k\,M_o + b}{M_o}}{\dfrac{k\,M_1 + b}{M_1}} = e^{-\dfrac{\rho A\,s_1\,b}{2\,m}}$$

for $s_o = 0$.

By transposition and substitution

*R.O. Pierce, A Short Table of Integrals, Ginn and Company, Boston, 1929.

This integration form was independently presented by Mr. James Bradley of LFD.

$$\frac{k\ M_o + b}{M_o}\ e^{\frac{\rho\ A\ b\ s_1}{2\ m}} = \frac{k\ M_1 + b}{M_1} \quad ,$$

$$R\ e^{Qs_1} = \frac{k\ M_1 + b}{M_1} \quad , \text{ and}$$

$$M_1 = \frac{b}{R\ e^{Qs_1} - k} \quad .$$

APPENDIX B

H-P PROGRAM FOR RETARDATION

This program requires the physicals of the projectile and the linear approximation of the C_D vs M curve. It includes a stepping feature within a loop which automatically decrements the range and repeats the calculation. The input is dimensioned in the units in common usage locally.

Input

R_1 Extreme range in meters
R_2 Initial Mach number
R_3 Shaft diameter in inches
R_4 Projectile weight in pounds
R_5 Intercept of C_D vs M curve
R_6 Slope of C_D vs M curve
R_7 Conversion constant = .000671
R_8 Range decrement

Output

Range in meters
Initial Mach number
Mach number at specified range
Retardation in ft/sec/km

```
001  *LBLE   21 15
002   RCL1   36 01
003   X=0?   16-43
004    RTN      24
005   PRTX     -14
006    CLX     -51
007   RCL2   36 02
008   PRTX     -14
009   RCL6   36 06
010      x     -35
011   RCL5   36 05
012      +     -55
013   RCL2   36 02
014      ÷     -24
015   STOA   35 11
016    CLX     -51
017   RCL3   36 03
018     x²      53
019   RCL7   36 07
020      x     -35
021   RCL5   36 05
022      x     -35
023   RCL4   36 04
024      ÷     -24
025   RCL1   36 01
026      x     -35
027     e^x     33
028   RCLA   36 11
029      x     -35
030   RCL6   36 06
031      -     -45
032   RCL5   36 05
033      ÷     -24
034    1/X      52
035   PRTX     -14
036   STOB   35 12
037    CHS     -22
038   RCL2   36 02
039      +     -55
040      1      01
041      1      01
042      2      02
043      0      00
044      0      00
045      0      00
046      0      00
047      x     -35
048   RCL1   36 01
049      ÷     -24
050   PRTX     -14
051    SPC   16-11
052   RCL1   36 01
053   RCL8   36 08
054      -     -45
055   STO1   35 01
056   GTOE   22 15
057    RTN      24
058    R/S      51
```

APPENDIX C

CALIBER NOMENCLATURE

Caliber nomenclature is widely used in aerodynamic expression as a dimensional convenience to compare performance parameters of geometrically similar models. It is usually referred to a linear scale representing the arithmetic ratio of a linear dimension to an arbitrary standard - most often the body diameter at the forward bourrelet - but has been employed to identify volumes*. Only a simple extension of the reasoning is required then to simultaneously de-dimensionalize the "mass" factor in a given expression and deduce a normalized system of mechanical units which permits a rational comparison of the dynamic properties of even geometrically dissimilar elements of machinery. Usually the context of discussion identifies the quantities as "mass cal", "inertia cal" "length cal", etc., although a complete lexicon of explicit and descriptive terms is available for this purpose.

For this report, the following correlation is employed:

$$\text{Length (cal)} = \frac{\text{linear dimension}}{\text{diametral dimension}}$$

$$\text{Weight (cal}^3\text{)} = \frac{\text{gravity weight}}{\text{gravity weight of unit volume of water}}$$

$$= \text{S.G.}$$

$$\text{Mass (cal}^2\text{ sec}^2\text{)} = \frac{\text{S.G.}}{\text{gravity acceleration}}$$

Thus, with force equal to mass times acceleration:

$$(\text{cal}^3) = (\text{cal}^2\ \text{sec}^2)\ \left(\frac{\text{cal}}{\text{sec}^2}\right)$$

*MacAllister, et al., "A Compendium of Ballistic Properties of Projectiles of Possible Interest in Small Arms", BRL Report No. 1532, February 1971, (AD #882117).

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